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Reduction of Disassembly Forces for Detaching Components with Solidified Assembly Connections

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Abstract

The disassembly of components with solidified assembly connections is often difficult to plan. A typical example can be found in the aviation industry, where turbine blades solidify in the turbine disc due to operational loads. The solidification of the joining partners has several causes such as thermal stress or high centrifugal forces so that the disassembly forces cannot be estimated exactly. The forces in manual disassembly, e.g. when striking the assembled part with a hammer, are often too high and thus difficult to control. An automated approach is investigated, in which a piezo stack actuator induces vibrations to the joined components and force amplitudes are reduced based on a simplified model of the solidification. For this purpose, simulations are presented to determine forms of excitation for the piezo actuator and to control the disassembly process.

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Keywords: Automation, Assembly Connections, Disassembly, Dissambly Forces, Turbine Blade, Vibrations

1. Introduction

The disassembly of a product initiates its regeneration and the disassembly ability is a key indicator for the sustainability and a resource-efficient recycling of the product. The assembly connections strongly influence a product's sustainability and define the disassembly characteristics of the product.
Disassembly processes can be divided into either detachable connections, such as screws or guides, or non-detachable connections such as welded connections [1]. The last mentioned are generally separated by destructive processes [2]. Generally, a destructive process is counterproductive when attempting to regenerate a product through preliminary disassembly. For that reason, only detachable connections are part of the research in this paper.

A fundamental challenge in the disassembly of detachable connections is the change of the degree of freedom of the assembly connection due to product operation. Typical causes for changes in the degree of freedom include broken screw heads and worn or soiled guides. During disassembly, these changes can result in further damage to the connecting partners due to undefined reaction forces, acting inside the connections of the joining partners. The risk of damage decreases with an improved quality of a disassembly process. A quality process is worthwhile especially in the aviation industry, where the regeneration of quality goods is indispensable. The disassembly of turbine blades as a quality good which solidifies in a turbine disc is investigated in this topic. With regard to the aim obtaining a controlled process, the question is, whether unknown quantities such as a solidification parameter can be described to avoid oversized disassembly forces. A promising approach to control these forces is to induce vibrations with an adaptive application.

2. Related Work

In general, in assembly and disassembly technology oscillations are considered annoying and are avoided by rigid structures. However, there are also technologies where vibrations are deliberately brought e.g. in the instances of handling technology such as vibratory feeders. Further, also approaches are found that take advantage of oscillations in joining as primary assembly technology.

Vibrations are used for reducing assembly forces, for example in the field of geotechnical and mining technology such as sonic drilling. Sonic drilling is a soil penetration

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technique that strongly reduces friction on the drill string. This is used e.g. for insertion of pipes in the ground. This principle, so-called vibratory driving, bases on the harmonic excitation of a ram body, where a structure rearrangement of the soil occurs. The vibrations cause a temporary reduction of porosity of the soil and thus the friction between soil and ram body (shaft friction). The method is suitable for different types of soil, such as sand, silt, and clay with inhomogeneous formations. Also, hard rocks can be pierced within limits. In this technology, the tools press forward under a slight pressure into the ground with an overlapped axial vibration in the range of 100 to 200 Hz [3]. In these methods for drilling into the soil, vibrations are used to reduce assembly forces, but it remains questionable whether the same force reduction effects can be exploited for detaching components with solidified assembly connections.

In the case of solidified connections and necessary detaching tools, screw connections were primarily examined in the research of disassembly technology. One of the main causes that leads to a solidification of screw connections is corrosion. In [4], the influence of corrosion on disassembly forces was examined for screw connections. The higher the corrosion class, the higher is the torque required for loosening a screw connection. For electronic equipment, surface corrosion can increase the loosening torque up to 45% [4]. The effects of solidification on disassembly time are illustrated in another publication [5]. As shown there, the duration increases significantly due to solidification and deformation of a screw. To design a tool which can be used to loosen solidified screw connections, a mathematical model was created that determines the energy required for disassembly [6]. Based on the estimated energy that is required to loosen the assembly connection, the corresponding disassembly tool induces vibrations in the object to create an additional acting surface through plastic deformation. Given the plastic deformation caused in some of the components, the disassembly method is partially destructive. The priority is to reduce the force transmission to the user of the tool and not primarily a component protection [7].

In other publications, the positive effects of higher frequencies in the production are used for a component friendly manufacturing. Ultrasonic machining applies superimposed ultrasonic vibrations in classic manufacturing processes such as drilling, milling, grinding, turning, etc. and it has less negatives effects on tool wear, machining forces, machinability, and surface finish. In particular, coupled vibration can make the machining of brittle materials, such as ceramics and glass easier. Also for the machining of metals, ultrasonic machining could come with advantages such as lower machining forces, lesser tool wear, and thinner chips. Ultrasonic machining also reduces the breakage of the tool during the process. Piezoelectric actuators are often used to provide adjustable mechanical vibrations. The transducer, generally designated as a converter, converts electrical energy into mechanical oscillation energy [8] [9]. Aim of this research is to use oscillation energy for disassembly with the prospect of being able to control the force amplitudes well. In order to adjust oscillations, a description of the acting forces in a disassembly connection is required. This is shown by the example of a turbine blade disassembly.

3. Case Study - Turbine Blades Disassembly

After an engine operation, turbine blades in a turbine disk are typical examples for solidified connections (Figure 1). Due to the high quality of the components, there is a great demand for automated solutions that increase the reproducibility of the disassembly process.

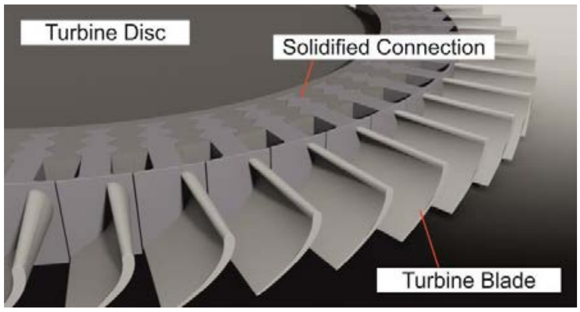

Figure 1: Turbine Blades with Turbine Disc

The last of many disassembly steps in a turbine disassembly is the manual separating of blade and disc. Depending on the type of turbine and turbine components, the removal processes distinguish to each other by the necessary detaching forces, which depend on the geometry of the connection profile. The high pressure turbine blades generally have a more jagged profile (fir tree profile - Figure 2 - left) connection to the turbine disc. The advantage of such a connection type is the distribution of the centrifugal forces onto several contact surfaces. In comparison, the low pressure turbine consists of a trapezoid prism connection (Figure 2-right).

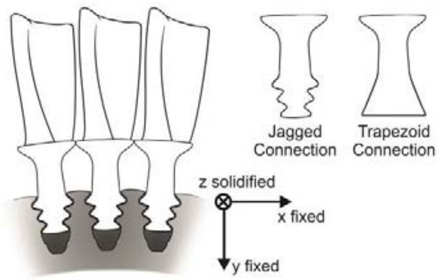

Figure 2: Connection geometry of Turbine Blades

The tight fit secures the turbine blades in radial and tangential directions, so that they only can be assembled and disassembled axially. The axial solidification between the foot of the turbine blade and disc blocks the axial degree of freedom and it may be the result of various causes. One possibility is that the high forces and temperatures occurring during engine operation stress the materials nearly to their resistance limits. Another possibility includes external forces such as weather conditions and other extraneous matters (for example sand), which entered in the turbine.

The degree of solidification, or the resulting forces acting in the connection, is typically unknown because the reasons are not obvious. Therefore, a targeted initiation of a force cannot be accurately planned for disassembly and the current disassembly process involves a manual beating to the blades out of the disc by a hammer [10]. But in this manner, there is insufficient control over the magnitude and location of the disassembly force. This could lead to damages or even to the loss of an expensive turbine blade. For example, edges of blades for carring damper elements can break off (Figure 3).

Figure 3: High-Pressure Turbine Blade - Institute of Turbomachinery and Fluid Dynamics, Leibniz University of Hannover

In summary, there is a high demand to eliminate non-reproducible process steps in manual disassembly in the aviation industry. Engine components, such as turbine blades, must be licensed, and therefore the requirements on component quality and reliability are very high. In order to automate a reproducible process, it is necessary to know the degree of solidification as a parameter to determine an optimal disassembly force, which is directly related to the solidification parameters.

4. Acting Forces in the Case of Solidified Assembly Connections

The essential disassembly parameters are set in relation to each other in order to control the process. Therefore, the relationship between disassembly force and the displacement of the turbine blade position in the disc should be determined during disassembly. For a qualitative process, the disassembly force should be reduced without increasing the duration of the process. To control the disassembly time, it is intended that the blade always moves during detaching with the same distance Δz in the guide (length l_F) by a force $F(t,z)$ (Figure 4 - right).

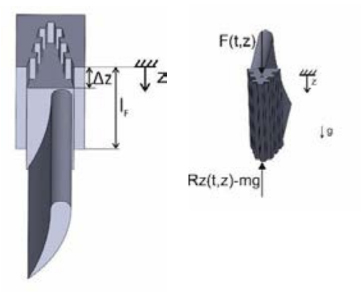

Figure 4: Relative Position Change of Joining Partners and Acting Forces during the Disassembly at a Turbine Blade

To control the relative movement of the joining partners, it is necessary to estimate the unknown reaction force $Rz(t,z)$. Given the various solidification causes, this often presents a challenge. Generally, the disassembly force $F(t,z)$ must exceed a maximum solidification force $Rz_{max}(z)$. The solidifying force is determined by the following parameters: 1. contact surfaces A_{KF} of the joining partners, 2. weight of the turbine blade mg, 3. pressure p of the components to each other, 4. coefficient of static friction μ. By means of these parameters, a function of a maximum solidification force is estimated, which depends on the position of the blade in the guide. This is done on the basis of a simplified model (Figure 5), in which only the contact surface during the disassembly process changes and the material-dependent coefficient of static friction and the pressure component of the joining partners to one another remain constant. The maximum solidification is described by:

$$Rz_{max}(z) = \mu p A_{KF}(z) \qquad (1)$$

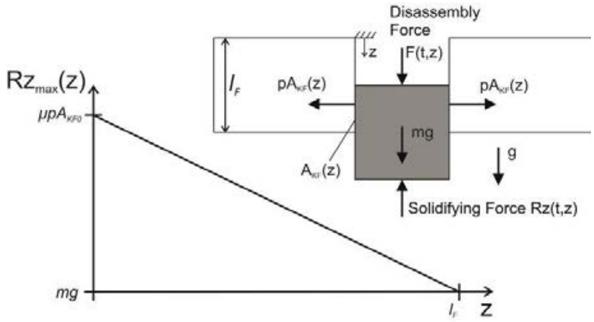

Figure 5: Simplified Solidification Model with the Function of Maximal Solidification (2)

Figure 5 indicates the graph of $Rz_{max}(z)$ as a function of the guide position. The amount of $Rz_{max}(z)$ in a (partially) assembled turbine blade has to be at least the gravitational force mg. Thus the function of $Rz_{max}(z)$, whereby the component pressure p is an unknown quantity, is given by:

$$Rz_{max}(z) = \mu p A_{KF0}\left(1 - \frac{z}{l_F}\right) + mg \qquad (2)$$

FE-Simulations confirm the curve profile of the reaction force (Figure 6). The internal pressure p has been simulated using an interference fit between blade and guide. An external displacement of a blade foot has been defined as a constraint condition and a static reaction force as the resulting solidification force was measured.

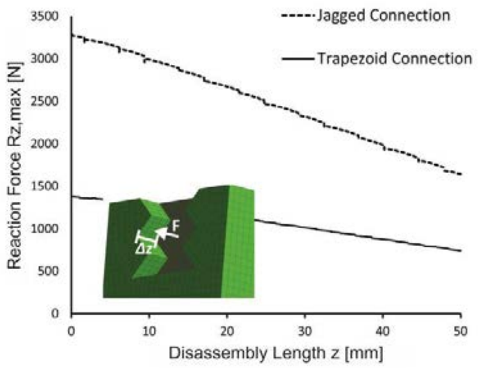

Figure 6: Course of Solidification Force in FE-Simulation

Figure 6 illustrates that the different profiles of $Rz_{max}(z)$ are linear and that the slope depends on the connection geometry in spite of simulating with a same contact surface A_{KF}. As expected, the resulting solidification in the fir tree connection is substantially higher than that of the trapezoid prism connection. The measured force $Rz_{max}(z)$ must be exceeded slightly in order to achieve a small disassembly force and thus a small component stress. Therefore, the relative movement between the joining partners is small. For a controlled disassembly, even though high forces are generated, vibrations in form of impacts are considered.

4.1 Benefits of Impacts in Disassembly

For a gentler disassembly with impulses, the amplitudes must exceed the solidification reaction force and be reduced as well as possible. For this purpose, the energy consumption of the disassembly process is taken into account. The required disassembling energy E_{ges} is described by the average solidification force $\overline{Rz}$ and the total disassembly displacement corresponds to the guide length l_F:

$$E_{ges} = \overline{Rz} \; * \; l_F \tag{3}$$

The average solidification force $\overline{Rz}$ by a constant foot position is given by (Rz_0 is the initial value of the solidification):

$$\overline{Rz} \approx \frac{1}{2}(Rz_0 - mg) \tag{4}$$

To exceed the maximum solidification, the advantages of a mechanical impact are illustrated. When two bodies collide, they typically exert strong forces on each other, but only for a short time. If an impulse of a body changes, a force acts on it caused by a collision. The shorter the time of this change in pulsation, the larger is the force. The performance of a vibrating disassembly tool slows in a very short time and thus the pulse changes. The average force, respectively, the time average of the force during this time interval is defined as [11]:

$$\{F\} = \frac{1}{\Delta t}\int_{t_A}^{t_E} F\,dt \tag{5}$$

t_E	=	End of impact
t_A	=	Start of impact
Δt	=	Duration of impact (t_E - t_A)

Thus, an impulse change over a very short period results in a very high force on the blade foot, despite a low average force. This fact with regard to the solidified assembly connection, allows two options. On the one hand, a piezo-stack actuator can generate a high average force with high amplitude and low frequency, so that a relatively large displacement Δz results. On the other hand, the average force amplitude can be reduced so that the maximum force per impulse overcomes just the displacement limit $Rz_{max}(z)$ and acts only for a very short time on the blade with a small step Δz in the guide. Combining this with an increased frequency leads to a consistent disassembly time with a significantly reduced force of amplitude compared to the first alternative (Figure 7).

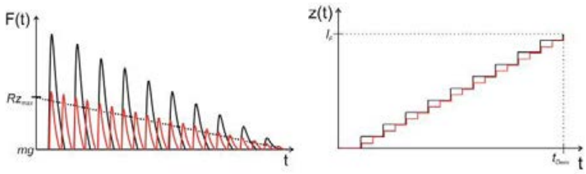

Figure 7: Reducing of Disassembly Force Amplitudes by an increasing frequency

With adaptive force amplitudes and a constant foot displacement Δz, the disassembly progress of the blade can be described by (6):

$$l_F = z_{ges} = f * t * \Delta z \tag{6}$$

f	=	Frequency of impacts
t	=	Time of disassembly
Δz	=	Blade step per impact

By combining (3) and (6) the total energy is:

$$E_{ges} = \frac{1}{2}(Rz_0 - mg) * f * t * \Delta z \tag{7}$$

Using equation (7), it can be shown that the energy depends on the average force $\overline{Rz}$ and the frequency f. It is not relevant whether the stamp of piezo stack actuator performs a sinusoidal motion with a constant $d \neq 0$ (Figure 8) or the impulse is caused by a pulse voltage excitation $d=0$. This finding allows to avoid additional distance sensors in the practical implementation and an anyway necessary force sensor ensures contact between actuator and blade.

The most important variable is the duration of the impact Δt to exert a high maximum force on the blade. In summary, the average force acting on the blade force is reduced significantly by a suitable frequency and an amplitude selection. Thus, the component connection can be detached more gently as with a continuous force.

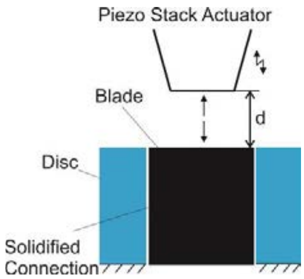

Figure 8: Piezo Actuator with Blade/Disc Connection

4.2. Determination of Frequency Area for Disassembly

In order to achieve the same total disassembly duration of a blade with a small foot step Δz, the impact frequencies are increased. Here the simulation gives a first estimate about the frequency level. Figure 9 shows the stress profiles in the turbine blade with different Δz.

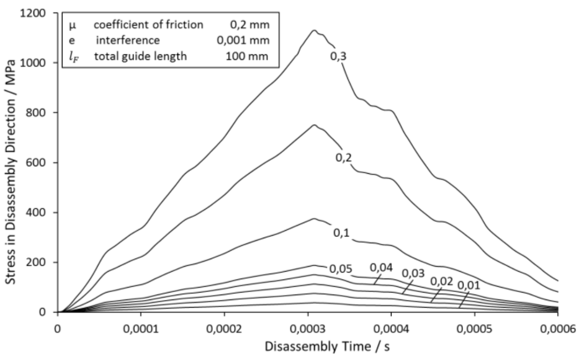

Figure 9: Stress in Turbine Blades with different Disassembly Impact Forces and Blade Step

The Figure shows that a small displacement Δz can reduce stress and therewith the disassembly forces significantly, resulting in a controlled and stress-free process. Table 1 shows how frequencies should be increased in order to keep the disassembly time constant.

Table 1: Needed Frequencies by Different Blade Step

Δz_1 [mm]	f [Hz]
0,01	1000
0,02	500
0,03	333
0,04	250
0,05	200
0,1	100
0,2	50
0,3	33

μ	Coefficient of Friction	0,2
e	interference	0,001 mm
l_F	Total Length	100 mm
t	total disassembly time	10 s

$$f = \frac{l_f}{t \cdot \Delta z} \quad \text{Disassembly frequency [Hz]}$$

4.3 Piezo Stack Actuator as a Disassembly Tool

To induce vibrations using a piezo stack actuator, a possibility to control the piezo force is described. The force is caused by an electrical voltage. The voltage amplitude u_p determines the change in length z_p and the level of the blocking force F_p (8). The variables α and c signify the force parameter and the stiffness of the piezotransducer, respectively [12].

$$F_p(t) = cz_p(t) - \alpha u_p(t) \quad (8)$$

In order to control the force, the distance must be kept constant. The easiest way to ensure a constant distance is a direct contact between stack actuator and the disassembly object before a voltage pulse. After initiation of a voltage, z_p is zero as long as the maximum solidification force is not exceeded and the joining partners are not moved relative to each other. So before a displacement starts, (8) can be simplified to:

$$F_p(t) = -\alpha u_p(t) \quad (9)$$

The dependency of the voltage of the time in (9) is transferred to the dependency of the position z in the guide as the minimum voltage, which is needed to get a displacement. A limit function at which the disassembly process starts, can described as:

$$Rz_{max}(z) = -\alpha u_{p,min}(z) \quad (10)$$

Furthermore, based on a given voltage at a test stand, it is possible to estimate the unknown solidification pressure p (11) for comparison with the interference fit of the simulations and convert it. Thus, the solidification can be implemented in the simulations with parameters that fit the real conditions.

$$p = \frac{\mu A_{KF0}}{u_p(z)\alpha}\left(\frac{z}{l_{Guide}} - 1\right) - mg \quad (11)$$

The above results show that it is possible to concretize the solidification which facilities adjusting the disassembly forces. The missing solidification parameters can be set up through to practical experiments, for which a test stand already exists, which allows to replicate various solidification rates.

5. Conclusion and Outlook

In contrast to the assembly in a joining task, unknown fits are typical in a disassembly of joined components. The problem was illustrated by the example of disassembly of turbine blades, which solidify in a turbine disc after an operation. The unknown parameters such as solidification or disassembly force prevent a reproducible disassembly. The new approach includes keeping the relative movement of the joining partners during the disassembly as small as possible. Due to high impact frequencies, the disassembly process is not slowed down. The force amplitudes are adjusted based on a new solidification model, which is proposed to describe the solidification with a parameter. Thus the minimum disassembly force can be quantified in the form of vibrations. The particular suitability of vibrations as disassembly forces was demonstrated and FE-simulations contained frequency ranges to detach the components gently from each other. However, the chosen solidification in the simulation needs to be assigned to a real turbine solidification, in order to obtain a conclusive quantification of a force difference of manual disassembly to the new method.

Prospectively, assumptions and simulation results will be validated at a test stand with a replica of a mating blade disc. Various solidification grades can be represented on the test stand. After validation, the missing parameter (11) can be measured and a "real" solidification can be added in the simulation so that the initial force can be predetermined for a real disassembly task. For that, further research is needed to assign the solidification of the real turbine to the test stand.

Based on the results, another approach is to apply impulses to the joined partners before disassembly. The impulse amplitude is slowly increased until a relative movement of the joined components sets in. The measured force at the starting point determines Rz_{max0} and thus the intercept and slope of $Rz_{max}(z)$. This knowledge can be implemented in a control of a disassembly tool. A robot could guide a tool that disassembly the blade over the disc circumference. A potential disassembly workplace for a fully automated turbine disassembly process is shown in Figure 10.

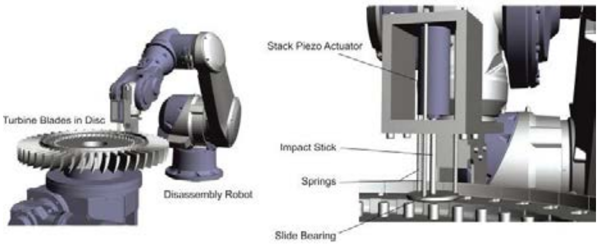

Figure 10: Example for an Automated Turbine Blades Disassembly Workplace (Robot Stäubli TX200)

The endeffector as the piezo-stack actuator of a disassembly robot provides in combination with the movability of the robot a great flexibility in the disassembly task. A slide bearing protects the actuator against shear forces and springs allow a follow from the tool to the disassembly progress of a blade. The workplace does not yet include the handling of the blades, which is taken into account in further work.

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